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Review

A Critical Review and Bibliometric Analysis on Applications of Ground Penetrating Radar in Science Based on Web of Science Database

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Abstract: Ground-penetrating radar (GPR) is an established technology with a wide range of applications for civil engineering, geological research, archaeological studies, and hydrological practices. In this regard, this study applies bibliometric and scientometric assessment to provide a systematic review of the literature on GPR-related research. This study reports the publication trends, sources of publications and subject categories, cooperation of countries, productivity of authors, citations of publications, and clusters of keywords in GPR-related research. The Science Citation Index Expanded (SCI-EXPANDED) and the Social Sciences Citation Index (SSCI), which can be accessed through the Web of Science Core Collection, are used as references. The findings report that the number of publications is 6880 between 2001 and 2021. The number of annual publications has increased significantly, from 139 in 2001 to 576 in 2021. The studies are published in 894 journals, and the annual number of active journals increased from 68 in 2001 to 215 in 2021. Throughout the study, the number of subject categories involved in GPR-related research fluctuated, ranging from 38 in 2001 to 68 in 2021. The research studies originated from 118 countries on 6 continents, where the United States and the People's Republic of China led the research articles. The top five most common keywords are ground-penetrating radar, non-destructive testing, geophysics, electrical resistivity tomography, and radar. After investigating the clusters of keywords, it is determined that civil engineering, geological research, archaeological studies, and hydrological practices are the four main research fields incorporating GPR utilization. This study offers academics and practitioners an in-depth review of the latest research in GPR research as well as a multidisciplinary reference for future studies.

Keywords: ground penetrating radar; bibliometric and scientometric assessment; bibliographic coupling; co-citation analysis

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1. Introduction

In the twenty-first century, mapping existing structures was a big issue for civil engineers. A crucial part of this procedure was extracting relevant information about the position, shape, and type of materials for embedded parts (e.g., sewers and reinforcing rebar). There are varieties of non-destructive testing (NDT) methods available, with ground-penetrating radar (GPR) being the most widely used in the civil engineering field [1,2]. GPR is a relatively new geophysical technology that has made significant progress in the recent decade. It can identify embedded things in structures without being destroyed since it uses electromagnetic waves and radargram processing technologies. Furthermore, it is portable equipment that can manage the full scanning procedure with just one operator [3]. The two key criteria of GPR are depth range and resolution. The signal may propagate farther with a lower center frequency of the GPR antenna, but the resolution in the shallower layers decreases. Higher frequencies do not penetrate deeply but provide higher resolution in shallower layers. Moreover, depth affects the size of the observable item. At shallow depths, little things can be observed, but as the depth range increases, an object's physical size must be big in order to be detected.

The antenna, storage unit, display unit, control unit, and various auxiliary devices (e.g., battery, car, and global positioning system (GPS)) are all part of the GPR system [4,5]. Figure 1 depicts the structure of a typical GPR system. The antenna is made up of a transmitter that sends electromagnetic waves into structures and monitors for echoes caused by changes in the material characteristics of the structure. The GPR signal has a wide variety of frequency components and commonly operates in the 10–5000 MHz range. The GPR receiver detects these reflected signals, which serve as the foundation for imaging inside the invisible structure [6]. A control unit delivers commands for sample time, repetition time, frequency, and other parameters. A graphical user interface (GUI) is included in the display unit, allowing numerous parameters to be visualized and adjusted. There can be a storage unit that can deliver data onto a PC or other processing units for additional analysis. Finally, depending on the type and technical requirements of the system, accessories such as GPS and wheels may be provided.

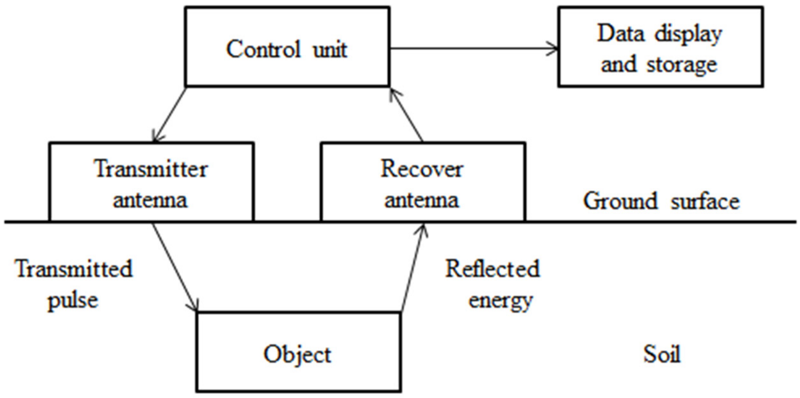

Figure 1. Components of a typical GPR system.

One of the most important applications of GPR in civil engineering is scanning buildings and common structural components [7]. GPR is also used to assess roads and pavements since it is one of the most used non-destructive approaches to obtain subsurface information on the structure of roads and pavements [8,9]. It may also be used for underground utility (e.g., pipes, tunnels, and sewers) detection [10,11]. Mineral exploration has major difficulty with complex geological conditions that could be investigated using this emerging technology [12]. In geology, GPR is used to detect permafrost, locate fractures or water-bearing zones, map shallow formations, and so on [13,14]. In archaeology, GPR is commonly employed for mapping buildings in historical sites [15,16].

Notwithstanding the significance of this geophysical technology, there is a dearth of comprehensive literature reviews to analyze the global research topics and future trends of GPR from a statistical standpoint. Bibliometric studies rely on the analysis of journals, authors, publications, author keywords, and collaboration between countries or institutions. The method is gaining popularity as a research tool for examining the knowledge domain or visualizing networks to offer a more comprehensive view of the subject [17]. Furthermore, such investigations aim to evaluate how research has evolved and provide some insights into future research trends [18–20].

The primary goal of this study is to perform a comprehensive literature analysis to study current and future global research trends in GPR research. The following sub-objectives are carried out to attain the primary goal: (1) establishing a framework for the reviewed literature; (2) conducting a science mapping analysis to identify time and geographical distribution, authorship, sources, keywords, and citations of publications in the field of GPR; (3) summarizing emerging research themes and determining current research gaps; and (4) proposing future directions in GPR research. The novelty of this study is as follows: (1) conducting objective review-based research in the GPR domain by applying bibliometric and scientometric assessment; (2) providing a more comprehensive analysis of research papers published across 20 years, from 2001 to 2021; (3) performing qualitative analysis that identifies current research status and emerging research trends; and (4) expanding the previous research study related to GPR research [21].

2. Research Methodology

In this review-based study, a holistic analytical approach that integrates quantitative and qualitative evaluations is applied to gain a better understanding of the study area and remove biased findings [22]. The flowchart of this review-based research study is divided into three primary steps, as illustrated in Figure 2. In this study, bibliometric and scientometric assessment has been applied as quantitative tools for examining GPR research from a variety of perspectives, including publication time and citations, author collaboration and productivity, subject categories and journals, relevant countries and institutions, and author keywords [23]. The final element of the study framework is qualitative analysis, which offers a thorough knowledge of the major topics in the GPR research study.

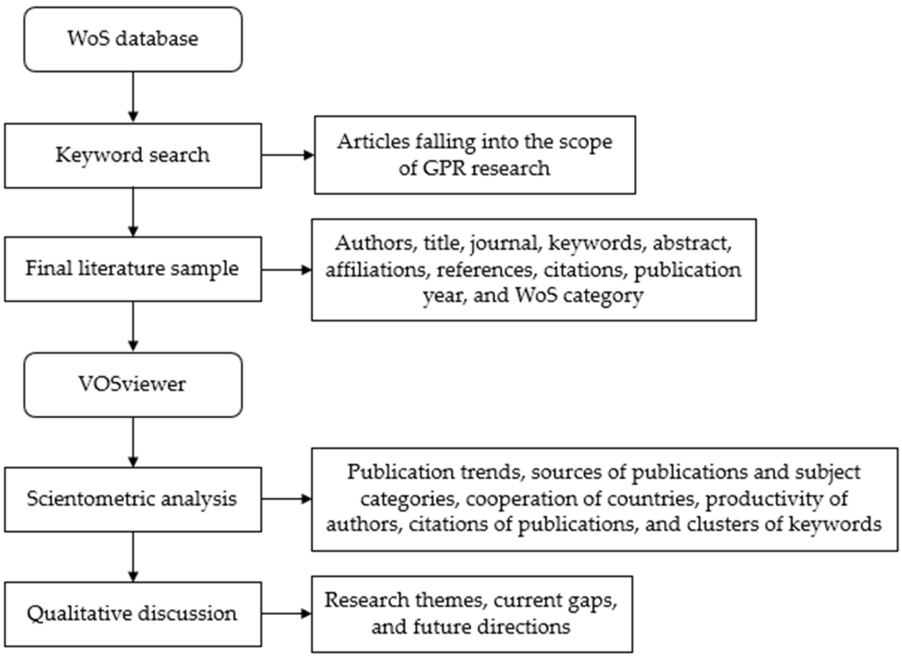

Figure 2. Review process for relevant papers.

Web of Science (WoS) is the most frequently used scientific literature database platform, with over 12,000 high-impact publications. Furthermore, this database is frequently used by scholars to gather accurate data for bibliometric studies [24,25]. As a result, the literature for this study is retrieved from the WoS database. Various phrases are examined to search for the targeted publications from the database. The utilized search phrases are GPR radar*, ground probing radar*, ground penetration radar*, ground penetrating radar*, GPR microwave*, GPR microwave*, geo-radar*, and georadar*. The asterisk indication guarantees that the search includes all relevant keywords. The targeted research and review publications are those published between 2001 and 2021. The conference papers are omitted because they lack the comprehensiveness of scientific content available in journal publications [26]. Science Citation Index Expanded (SCI-EXPANDED) and the Social Sciences Citation Index (SSCI) are chosen as citation indexes, and English is selected as the publishing language. Records related to the authors, article title, source title, author keywords, abstract, cited references, citations count, publisher, publication year, and WoS category of 6880 papers are downloaded as plain text (on 23 December 2021) from the database.

Bibliometric and scientometric assessment can be accomplished using many software applications such as Bibexcel, CiteSpace, VOSviewer, and VantagePoint. In this research, MS Excel is used to do the standard data analysis (such as publication trends, subject categories, journals, authors, nations, institutions, and keywords). The co-occurrence, bibliographic coupling, and co-authorship networks are developed using VOSviewer software (version 1.6.17) because of its aptitude for knowledge mining and visualization of vast networks (www.vosviewer.com; accessed on 23 December 2021 [27]). Kessler [28] was the first to use the term bibliographic coupling to characterize the thematic closeness between two research studies. Although bibliographic coupling was designed to locate articles with comparable research viewpoints, it may also be extended to other sources, such as authors and journals [29,30].

VOSviewer software visualizes three different formats of maps: network, overlay, and density visualization. The elements in the network visualization are represented by nodes where the size of each node reflects its weight and degree of importance. In addition, a node's color is determined by the cluster to which it belongs. The correlation between nodes is inversely proportional to their distances. The overlay visualization is similar to the network visualization, except that the elements are colored using a scale bar that displays the scores of clusters/items with respect to specific aspects (e.g., publication year). The density visualization shows how dense an object is at a specific point [31]. The density can be presented individually for each cluster to which the items belong (cluster density view) or without taking this distinction into account (item density view). However, network visualization is used in this study for brevity and visualization.

3. Results and Discussion

3.1. Publication Trends

The search yields 6880 publications during the twenty years from 2001 to 2021. The number of annual publications has increased significantly, from 139 in 2001 to 576 in 2021. Between 2001 and 2005, the annual number of articles was fewer than 200, with an average of around 160 each year. The annual number of publications climbed in 2006, reaching 219 compared to 173 in the previous year. There are around 258, 388, and 525 articles each year on average in the years 2007–2011, 2012–2016, and 2017–2021, respectively (Figure 3). In terms of the yearly total number of citations, Figure 3 shows an uneven trend: the three greatest values were 7659, 7548, and 7284 citations in 2007, 2013, and 2014, respectively. However, after 2014, the annual number of citations has steadily fallen, achieving 494 in 2021. This can be attributed to the fact that the more recent papers have had less time to be referenced.

3.2. Sources of Publications and Subject Categories

GPR papers were published in 894 journals between 2001 and 2021, illustrating the many disciplines and areas involved. Annually, the number of active journals increased from 68 in 2001 to 215 in 2021. As depicted in Table 1, the influence of these journals is quantified using four indicators; the number of publications, the average publication year, the average citations, and the average normal citations. The top five active journals in GPR-related research are the *Journal of Applied Geophysics*, *IEEE Transactions on Geoscience and Remote Sensing*, *Near Surface Geophysics*, *Remote Sensing*, and *Geophysics*, with 401, 316, 231, 199, and 198 total publications, respectively. These journals publish a total of 19.5% of the total articles, demonstrating the importance of these publications for GPR-related research. Figure 4 illustrates the annual number of publications for the five most productive journals. It demonstrates that each journal experiences yearly fluctuations in the number of published articles, with multiple peaks that tend to converge in the same periods, such as those in 2003, 2005, and 2010.

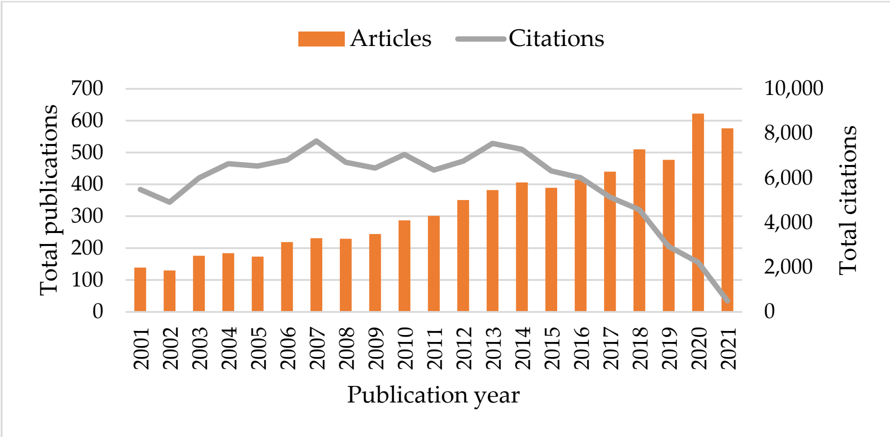

Figure 3. Trends of GPR-related publication outputs from 2001 to 2021.

Table 1. Top 5 most productive journals in GPR research between 2001 and 2021.

Journal	Publisher	Impact Factor (2021)	Number of Publications	Average Publication Year	Total Citations	Average Citations	Average Normal Citations
Journal of Applied Geophysics	Elsevier	2.121	401	2012.66	8052	20.08	1.04
IEEE Transactions on Geoscience and Remote Sensing	IEEE	5.600	316	2011.79	9365	29.64	1.42
Near Surface Geophysics	Wiley	2.033	231	2011.80	2525	10.93	0.54
Remote Sensing	MDPI	4.848	199	2019.11	1276	6.41	0.98
Geophysics	SEG Library	2.928	198	2011.19	4421	22.33	0.97

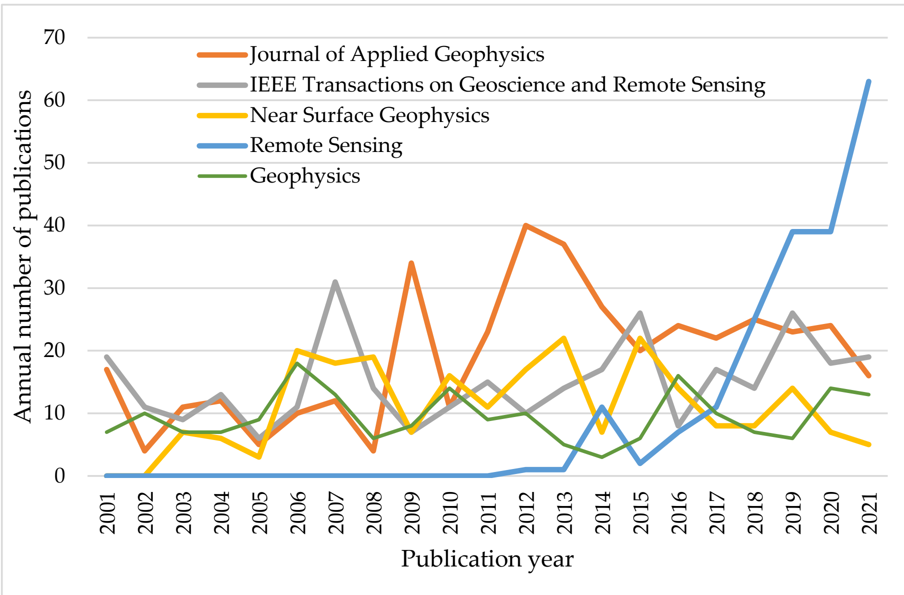

Figure 4. Number of annual publications by the five most active journals.

The top two most productive journals also have the highest number of total citations. For instance, the *IEEE Transactions on Geoscience and Remote Sensing* journal achieves the highest total citations of 9365, followed by the *Journal of Applied Geophysics* (8052 citations). However, journals with the highest average citations per article are not among the top three most productive or cited documents: *Computer Physics Communication* has the most (109.67), followed by *Tree Physiology* (94.75) and *Earth-Science Reviews* (80.67). On the other hand, articles published in *IEEE Transactions on Geoscience and Remote Sensing* have garnered an average of 29.64 citations per article, showing that GPR research papers published in these journals have had a significant impact on this subject.

Based on the average normal citations indicator, *IEEE Transactions on Industrial Informatics* (10.33) is shown to be the most significant journal in this study subject. This indicator is computed by dividing the total number of citations by the average number of citations published each year. It is used to deduce that older texts are not always cited more frequently than newer releases [32]. Furthermore, while having the largest research output, the *Journal of Applied Geophysics* is not regarded as the most fruitful journal since it does not have the highest average normal citations. The most recent studies are published in *IEEE Access*, *Water*, and *Remote Sensing* journals. The *IEEE Aerospace and Electronic Systems Magazine* and *IEE Proceedings—Radar*, *Sonar* and, *Navigation* journals, on the other hand, are no longer active in this study arena.

Figure 5 presents the prominent journals on the topic of GPR. The minimal threshold values are established at three articles and thirty citations. It was found that 251 out of 894 journals matched these criteria. Each journal is distinguished by a circle whose size is proportionate to the number of published articles. The distance between circles indicates the strength of the link with the other journal, such that the shorter distance indicates a stronger connection. Furthermore, the colors of clusters refer to the research topics such that journals belonging to the same cluster cover similar themes. For instance, 77 journals that primarily publish articles on earth sciences, geology, landslide, and sedimentology make up the largest red cluster. A total of 67 Journals that publish articles on applied geophysics, structure, and infrastructure are represented by the green cluster. The blue cluster, comprising 51 journals, includes research on glaciology, atmosphere, hydrology, and planetary and space science in the GPR-related domain.

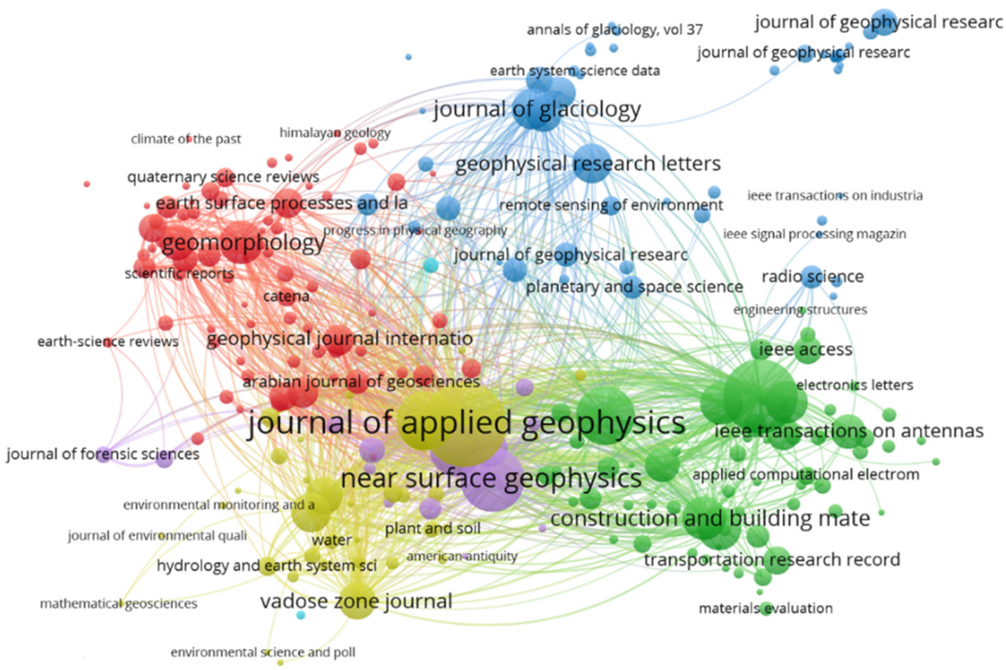

Figure 5. Bibliographic coupling analysis for the active journals.

Throughout the study, the number of WoS categories involved in GPR-related research fluctuated, ranging from 38 in 2001 to 68 in 2021. A large number of involved categories is dependent on the fact that publishing journals might cover numerous WoS categories. As shown in Figure 6, Geosciences, Multidisciplinary is the most important (2491 articles, or 17.51% of the total), followed by Geochemistry and Geophysics (1393 articles, or 9.79%), Engineering, Electrical, and Electronic (1152 articles, or 8.10%), Remote Sensing (857 articles, or 6.02%), and Imaging Science and Photographic Technology (803 articles, or 5.64%). These five categories account for 45.66% of all GPR-related research articles.

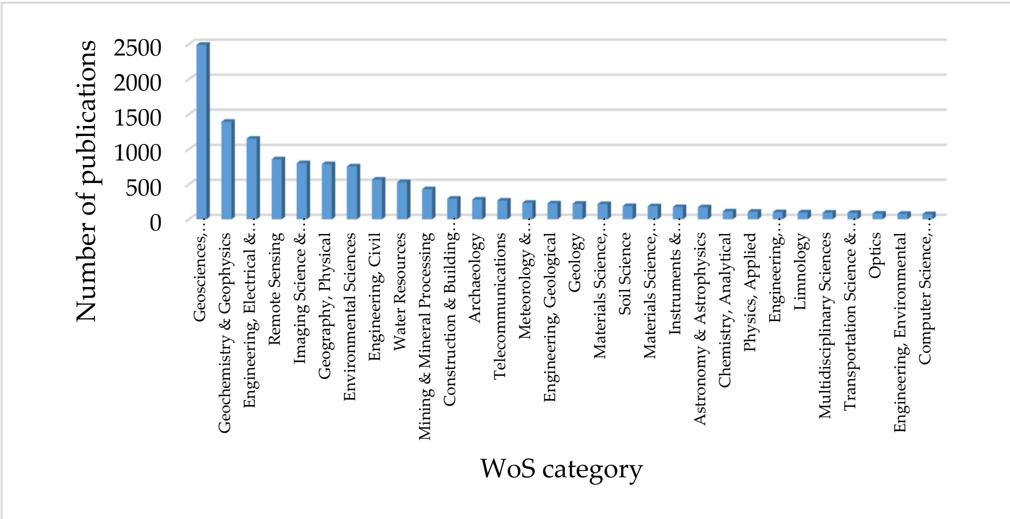

Figure 6. Distribution of top thirty WoS categories involved in GPR-related research.

After examining the growth trends of the five most important categories, it is clear that, while the trends show a general increase in the number of articles published, the scientific interest in each category has shifted over time (Figure 7). The Geosciences, Multidisciplinary and Geochemistry, and Geophysics categories have switched places multiple times over the years. The same applies to Geochemistry and Geophysics and Engineering, Electrical, and Electronic categories. In addition, there have been some significant changes in the number of articles published, such as the peaks in the Geochemistry and Geophysics category in 2007 and the sudden increase in the number of articles published in the Geosciences, Multidisciplinary category from 2011 onwards.

3.3. Country and Institution of Publications

Due to the lack of author address information in 24 (0.34%) of the 6880 papers, these data have been removed from the analysis of the publishing country and institution of research outputs. In the period 2001–2021, the GPR research encompasses 118 countries on six continents from all over the world. The six continents are arranged in the following order: Europe (43 nations), Asia (34 nations), Africa (18 nations), South America (10 nations), North America (9 nations), and Oceania (4 nations). It is determined that 59 countries (50.0%), 14 countries (11.86%), and 45 countries (38.14%) produced fewer than 10 articles, between 10 and 20 articles, and more than 20 articles, respectively. With 2002 research outputs (20.16%), the United States is the top productive country (see Table 2). With 959 articles (9.66%), the People's Republic of China comes in second but is still a long way behind the first. Italy (732, 7.37%), Germany (583, 5.87%), England (540, 5.44%), France (463, 4.66%), and Canada (408, 4.11%) are among the nations with at least 400 publications. Because both developing and developed countries are rated among the top ten countries, academic contributions are not solely dependent on economic progress. Furthermore, the articles have a global reach because they are scattered across three continents: North America, Asia, and Europe.

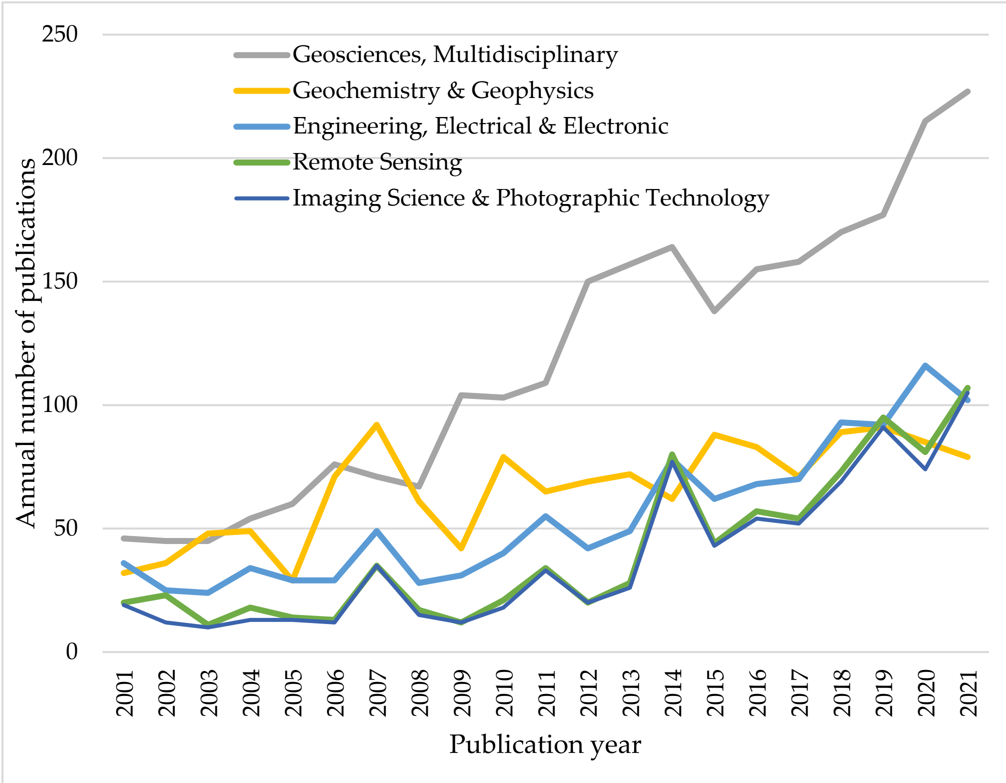

Figure 7. Number of annual publications in the top five WoS subject categories.

Table 2. Top 5 most active countries in GPR research between 2001 and 2021.

Country	Number of Publications	Average Publication Year	Total Citations	Average Citations	Average Normal Citations
United States	2002	2012.58	41,744	20.85	1.11
People's Republic of China	959	2016.75	9372	9.77	1.08
Italy	732	2013.69	12,193	16.66	1.02
Germany	583	2013.47	12,825	22.00	1.24
England	540	2013.49	12,054	22.32	1.50

Regarding the average publication year, the most recent studies are published in Qatar (2018.75), Cyprus (2018.71), and Vietnam (2018.64). The United States (41744), Germany (12825), Italy (12193), England (12054), and the People's Republic of China (9372) attain the highest total citations among other countries. Despite that, Syria, the country with the highest average citations (42.00), is not among the top-five most productive or cited countries. Concerning the average normal citations indicator, Kyrgyzstan (2.06) is the most significant country in this study subject.

The bibliographic coupling analysis for the active countries involved in GPR research is illustrated in Figure 8. Countries with at least three articles and thirty citations are included in the study. The network comprises 81 countries from a total of 118. It is worth noting that the countries are represented by nodes, where the size of each node indicates the total number of articles produced by each country. Meanwhile, the line thickness represents the strength of the cooperation link between the two countries. Malaysia (1.88), Oman (1.80), and Scotland (1.70) have the greatest influence on the average normal citation indicator, followed by Portugal (1.50), England (1.50), and Northern Ireland (1.45). The United States partners with the majority of nations, including the People's Republic of China, France, and Switzerland. Italy, which co-authored papers with the top productive countries, worked more closely with the People's Republic of China, Greece, and Algeria. Similarly, Switzerland, which coordinated with most of the other nations in the network, has Norway, Sweden, and Austria as its primary collaborators. All of these findings suggest that GPR research greatly encourages cross-national collaboration.

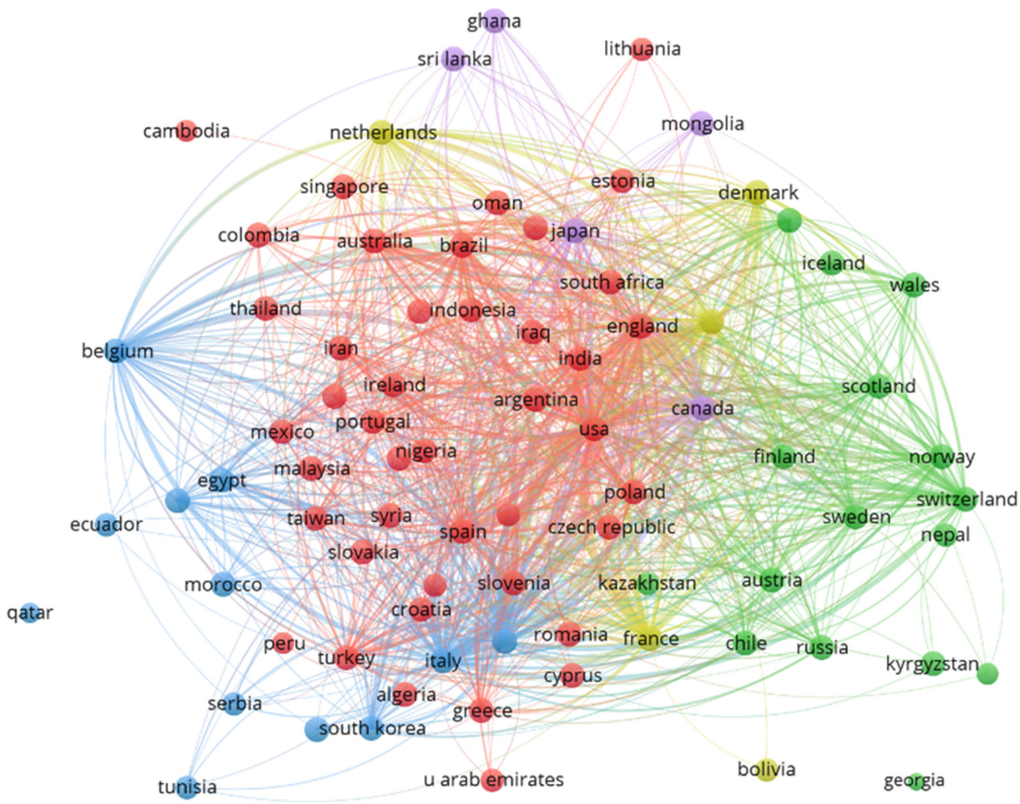

Figure 8. Bibliographic coupling analysis for the active countries.

The contribution of the institution has been assessed based on the affiliation of the article's authors. The institutions are determined by counting the total articles ascribed to a certain institution. GPR-related research is supported by 4714 institutions in total. The analysis includes organizations with at least three papers and thirty citations. Out of the total institutions, 889 organizations satisfy these criteria and are incorporated into the network (see Figure 9). It should be noted that the organizations are represented by nodes, with the size of each node indicating the total number of articles published by each organization. Meanwhile, the thickness of the line symbolizes the strength of the two organizations' cooperation relationship. The Chinese Academy of Sciences works with the vast majority of organizations, including Penn State University, the University of Waterloo, and Ohio State University. Meanwhile, the University of Wisconsin collaborates more closely with Boston University and the University of Copenhagen. All of these data indicate that GPR research promotes cross-national collaboration.

Table 3 depicts the top-five institutions that have been active in the last 20 years. The Chinese Academy of Sciences is the most productive among the main organizations, with 169 papers. The other four organizations came from four different countries (i.e., Italy, Holland, United States, and Germany); National Research Council is the most productive, with 116 papers, followed by Delft University of Technology (91), University of Illinois (88), and Forschungszentrum Jülich (85). With regard to the average publication year, Sun Yat-sen University (2019.92), Chongqing Jiaotong University (2019.80), and Central South University (2019.70) published the most recent studies. Delft University of Technology (2784), University of Leeds (2583), Forschungszentrum Jülich (2427), Chinese Academy of Sciences (2357), and Université Catholique de Louvain (2343) obtain the highest total citations among other organizations. However, organizations with the highest average citations are not among the top five most productive institutions: the University of North Dakota (50.50), the University of California, Berkeley (47.69), and the National Center for Atmospheric Research (46.29). Based on the average normal citations indicator, the Nanjing University of Aeronautics and Astronautics (25.72) is the most significant organization in this study subject. Furthermore, while having the largest research output, the Chinese Academy of Sciences (1.26) is not regarded as the most fruitful organization since it does not have the highest average normal citations.

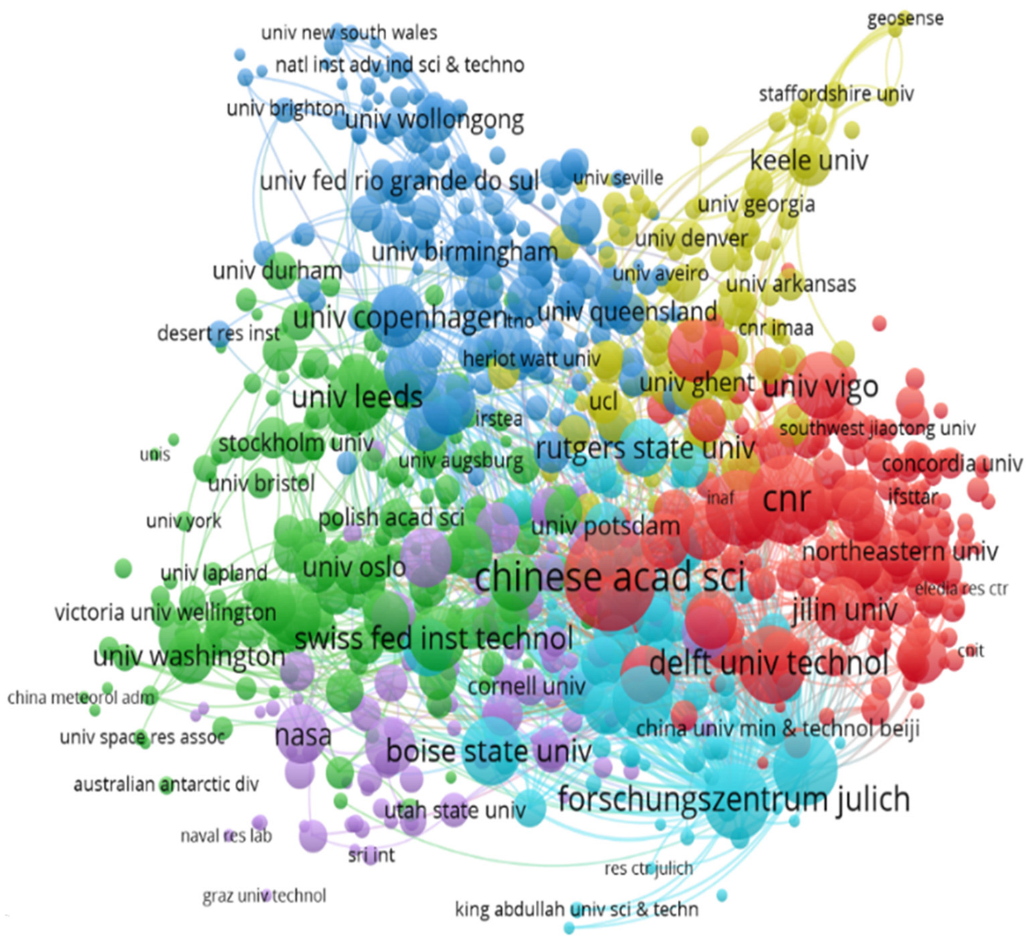

Figure 9. Bibliographic coupling analysis for the active organizations.

Table 3. Top 5 most active institutions in GPR research between 2001 and 2021.

Institution	Country	Number of Publications	Average Publication Year	Total Citations	Average Citations	Average Normal Citations
Chinese Academy of Sciences	China	169	2016.35	2357	13.95	1.26
National Research Council	Italy	116	2012.61	2339	20.16	1.05
Delft University of Technology	Holland	91	2010.84	2784	30.59	1.29
University of Illinois Urbana-Champaign	United States	88	2012.77	2207	25.08	1.43
Forschungszentrum Jülich	Germany	85	2013.94	2427	28.55	1.57

3.4. Productivity of Authors

Nineteen thousand thirty-seven individual authors are participating in GPR-related research, and the average cooperation index (i.e., number of authors per article) is 4.4. Table 4 depicts the quantitative measures of the most significant scholars. S. Lambot from the Université Catholique de Louvain and F. Soldovieri from the Italian National Research Council are the most productive authors, with 63 articles, followed by H. Vereecken from the Forschungszentrum Jülich, with 47 articles. According to the average publication year, X. Liu and D. Kumlu are among the most recently active researchers. Based on the total citations, S. Lambot, F. Soldovieri, H. Vereecken, J. Van Der Kruk, and Y. Rubin receive a total of 1547, 1271, 1118, 1027, and 1022 citations, respectively. Several scholars in the same cluster receive the same average normal citations. For example, C. Le Bastard and Y. Wang have an average normal citation of 0.74. This shows that these scholars made equal contributions to the scientific field. Furthermore, different groups of researchers differ in terms of the average normal citations. This suggests that these researchers collaborated with other teams or worked alone to develop new collisions.

Table 4. Top 5 most productive authors in GPR research between 2001 and 2021.

Scholar	Affiliation	Number of Publications	Average Publication Year	Total Citations	Average Citations	Average Normal Citations
S. Lambot	Université catholique de Louvain	63	2013.97	1547	24.56	1.37
F. Soldovieri	Italian National Research Council	63	2013.06	1271	20.17	1.18
H. Vereecken	Forschungszentrum Jülich	47	2014.64	1118	23.79	1.33
R. Persico	Institute for Archaeological and Monumental Heritage	43	2012.55	747	17.37	0.85
J. Van Der Kruk	Forschungszentrum Jülich	42	2014.29	1027	24.25	1.39

The bibliographic coupling for the most productive authors is illustrated in Figure 10. 1477 out of 19,037 authors meet the minimal criterion of three publications and thirty citations. The node size and color represent an author's number of articles and the membership cluster, respectively. Meanwhile, the distance between circles indicates the strength of the relationship between authors. In general, the shorter the distance, the stronger the connection based on bibliographic coupling. In other words, authors who are close to each other tend to cite the same publications and vice versa. The lines connecting between nodes are represented such that the thicker line indicates a greater bibliographic coupling between the two authors. The researchers are classified into seven clusters, and the size of each cluster ranges from 15 to 324. These clusters reflect the research network of academics in GPR research, such as the research group of G. Leucci, X. Comas, and E. Forte.

The co-authorship map for the influential researchers is illustrated in Figure 11. Because not all of these researchers collaborated, the cooperation network has only 721 authors. There exist 38 clusters that range in size from 3 to 77 scholars. There is a clear distinction between co-authorship and bibliographic coupling networks. The researchers in a particular co-authorship cluster may belong to a larger cluster of bibliographic coupling that comprises authors from other co-authorship clusters. For instance, F. Soldovieri is a member of the green cluster in the co-authorship map, with 41 authors. The same author, on the other hand, is a member of a larger green cluster in the author bibliographic coupling, with 266 researchers.

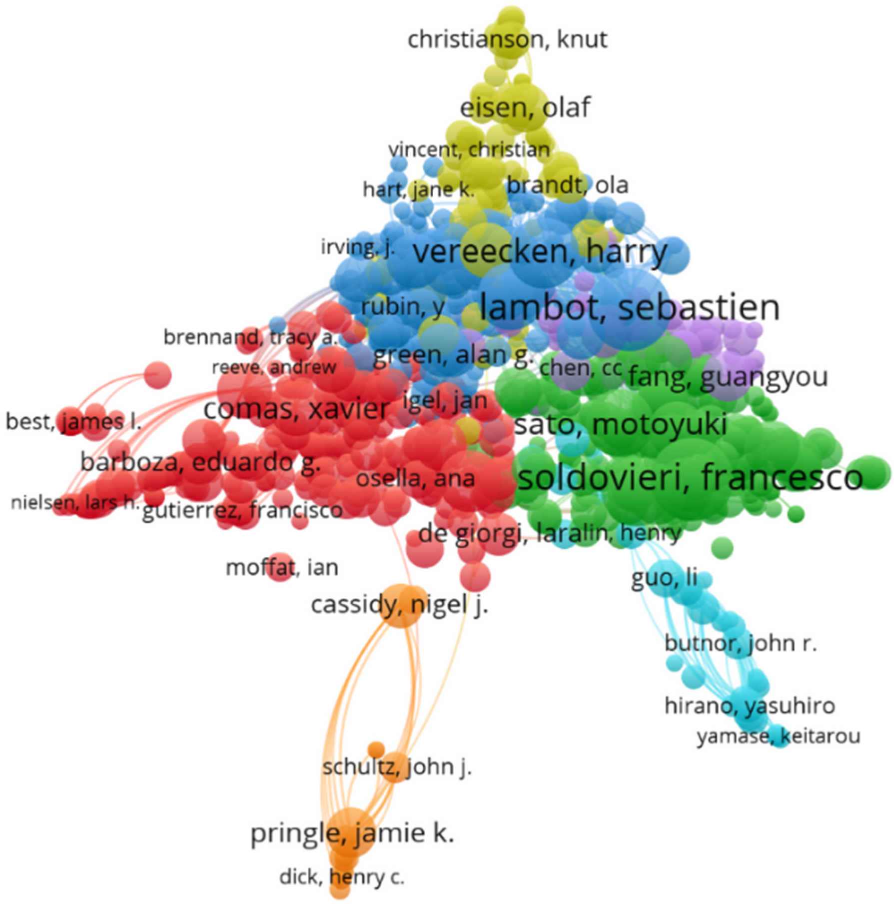

Figure 10. Bibliographic coupling analysis for the active authors.

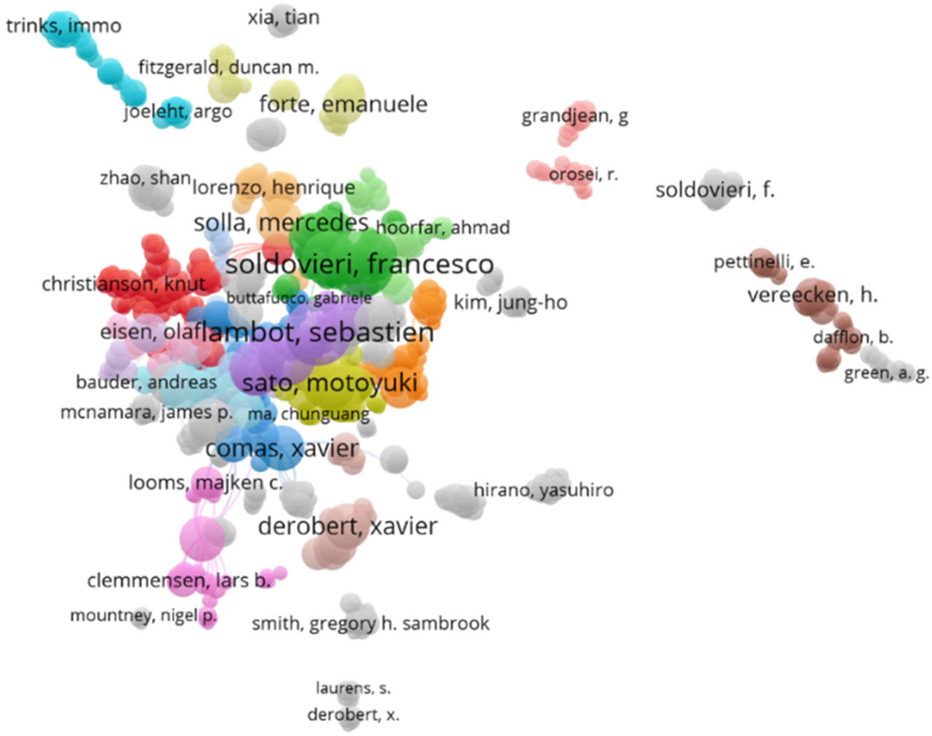

Figure 11. Co-authorship analysis for the most productive authors.

3.5. Citations of Publications

The total citation count is gathered from the Web of Sciences Core Collection (23 December 2021). A total of 470 out of 6880 papers receive at least 50 citations. The top five most-cited publications are listed in Table 5. Giannopoulos [33] is the first most referenced article (409 citations). The paper discussed the foundations of GPR operation, in addition to presenting a software tool for modeling GPR responses from complex targets (GprMax). Yoshikawa and Hinzman [34] is the second most referenced article (334 citations). Lambot et al. [35], which was referenced 299 times, is the third most cited article. Warren et al.'s [36] publication entitled "gprMax: Open source software to simulate electromagnetic wave propagation for ground penetrating radar" came in fourth place with 293 citations. Finally, Gurbuz et al.'s [37] article, which was referenced 234 times, is the fifth most cited article.

Table 5. Top 5 most influential publications in GPR research between 2001 and 2021.

Scholars	Title	Journal	Impact Factor 2021	Publication Year	Total Citations	Normal Citations
Giannopoulos [33]	"Modelling ground penetrating radar by GprMax"	*Construction and Building Materials*	6.141	2005	409	11.32
Yoshikawa and Hinzman [34]	"Shrinking thermokarst ponds and groundwater dynamics in discontinuous permafrost near Council, Alaska"	*Permafrost and Periglacial Processes*	4.368	2003	334	10.29
Lambot et al. [35]	"Modeling of ground-penetrating radar for accurate characterization of subsurface electric properties"	*IEEE Transactions on Geoscience and Remote Sensing*	5.600	2004	299	8.74
Warren et al. [36]	"gprMax: Open source software to simulate electromagnetic wave propagation for ground penetrating radar"	*Computer Physics Communications*	4.390	2016	293	20.97
Gurbuz et al. [37]	"Compressive sensing for subsurface imaging using ground penetrating radar"	*Remote Sensing*	4.662	2009	234	3.93

3.6. Cited References

When two studies cite one or more documents in common, this is known as bibliographic coupling. The bibliographic coupling strength is higher when there are more common citations in the referring works, detecting the subject similarity between the two studies. On the other side, co-citation analysis overcomes the shortcomings of bibliographic coupling by considering document citations that change over time to assess the similarity between articles. Two documents are said to be co-cited when they acquire a citation from the same third document [38].

Out of 149,276, 1004 cited references are extracted and grouped into seven clusters based on a criterion of at least 20 co-citations. Table 6 presents the top five most co-cited references. Davis and Annan [39] is the most cited reference (741 citations). The article demonstrated the ability to apply radar to map the stratigraphy of soil and rock. Neal [40] is the second most cited reference (491 citations). This research was concerned with studying the principles and problems of applying GPR in sedimentology. Daniels [41], which was referenced 453 times, is the third most cited reference. This article discussed the general system considerations, modeling aspects, applicability in different soil types, modulation techniques, and various technology applications. Jol's [42] article, which was referenced 423 times, is the fourth most cited reference. This research discussed the fundamental theory and current developments of GPR for different applications. Finally, Huisman et al.'s [43] publication came in fifth place with 334 citations. This article provided a detailed review of GPR technologies for measuring soil water content.

Table 6. Top 5 most cited references in GPR research between 2001 and 2021.

Scholars	Title	Publication Year	Total Citations
Davis and Annan [39]	"Ground-penetrating radar for high-resolution mapping of soil and rock stratigraphy"	1989	741
Neal [40]	"Ground-penetrating radar and its use in sedimentology: Principles, problems and progress"	2004	491
Daniels [41]	"Ground penetrating radar"	2004	453
Jol [42]	"Ground penetrating radar: Theory and applications"	2009	423
Huisman et al. [43]	"Measuring soil water content with ground penetrating radar: A review"	2003	334

3.7. Author Keywords in Publications

Author keywords can aid in grasping the patterns in a certain subject [44]. As a result, the author's keywords are investigated to examine the most important themes in the articles. A portion as large as 5117 (74.4%) of the 6880 total articles features one or more keywords, whereas the remaining 1763 (25.6%) articles do not incorporate any keywords. The majority of articles (1574; 22.9%) have five keywords (Figure 12).

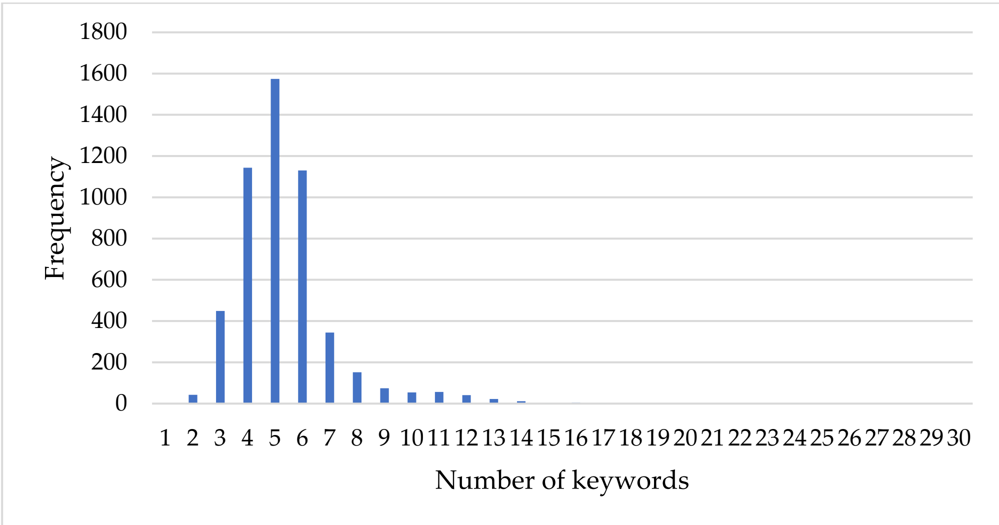

Figure 12. Statistical distribution of the keywords in GPR research publications.

There are a total of 13,626 occurrences of 27,499 unique author keywords. The 50 most common terms (0.37%) are thoroughly examined to obtain a more detailed look. These terms refer to some major "hot" issues, such as geophysics (e.g., electrical resistivity tomography), archaeological investigations (e.g., archaeology and cultural heritage), civil engineering (e.g., landmine detection and concrete), geology (e.g., stratigraphy and geomorphology), and hydrological research (e.g., hydrogeophysics, soil water content, soil, water content, and permafrost).

Keyword co-occurrence networks are one of the most prominent linguistic networks examined in the past. These networks are used to discover the semantic similarity between phrases [45]. In addition, they are used to reveal information about knowledge structures and their temporal evolution in a changing research topic [46]. The author keywords' and 'full counting' approaches are used to display the co-occurrence network. Some parameters in the VOSviewer, such as the minimum number of term occurrences, are adjusted to ensure building the map with several terms that represent the article content. When the frequency of keywords in the network map is adjusted to 10,230, 13,626 of the keywords are chosen. In addition, a thesaurus text file is inserted for combining multiple spellings of the same phrase (e.g., antennas and antenna, electrical resistivity tomography (ERT), and (FDTD) finite-difference time-domain). Furthermore, it could be useful for deleting irrelevant words (e.g., Egypt and Italy) or merging different terms referring to the same concept (e.g., numerical models and numerical modeling).

A co-occurrence map that includes 230 keywords for the whole period (2001–2021) is developed in Figure 13. This map provides an overview of GPR research and subfields with their interdependencies. The diameter of a circle and the size of labels show the occurrences of phrases. Meanwhile, the colors of the nodes reflect the clusters such that the phrases that often co-occur are clustered together on the map. Finally, the distances between nodes show the connections between the keywords. Furthermore, the keywords are organized into twelve clusters. Leading words identify each of these clusters. The keywords in the largest five clusters are described in this sub-section. The largest red category (36 items) includes keywords such as landmine detection, buried object detection, and permittivity. The second green cluster (31 items) includes phrases such as archeological prospection, geoarchaeology, monitoring, and geographic information system (GIS). The third blue cluster (27 items) comprises many keywords such as finite difference time domain, image processing, and tomography. The fourth yellow cluster (24 items) is responsible for topics related to mountain permafrost, rock glacier, soil, and seismic reflection. The fifth purple cluster (24 items) includes terms such as glacier, hydrology, ice, and snow. Within the same cluster, geophysics and electrical resistivity tomography are all significantly connected. On the contrary, there is no relationship between other terms in the same cluster, such as ice and radar signal processing. Furthermore, significant relationships between terms from different clusters, such as non-destructive testing, concrete, and condition assessment, may exist. This demonstrates the capacity of co-occurrence networks to determine the extent of a given area.

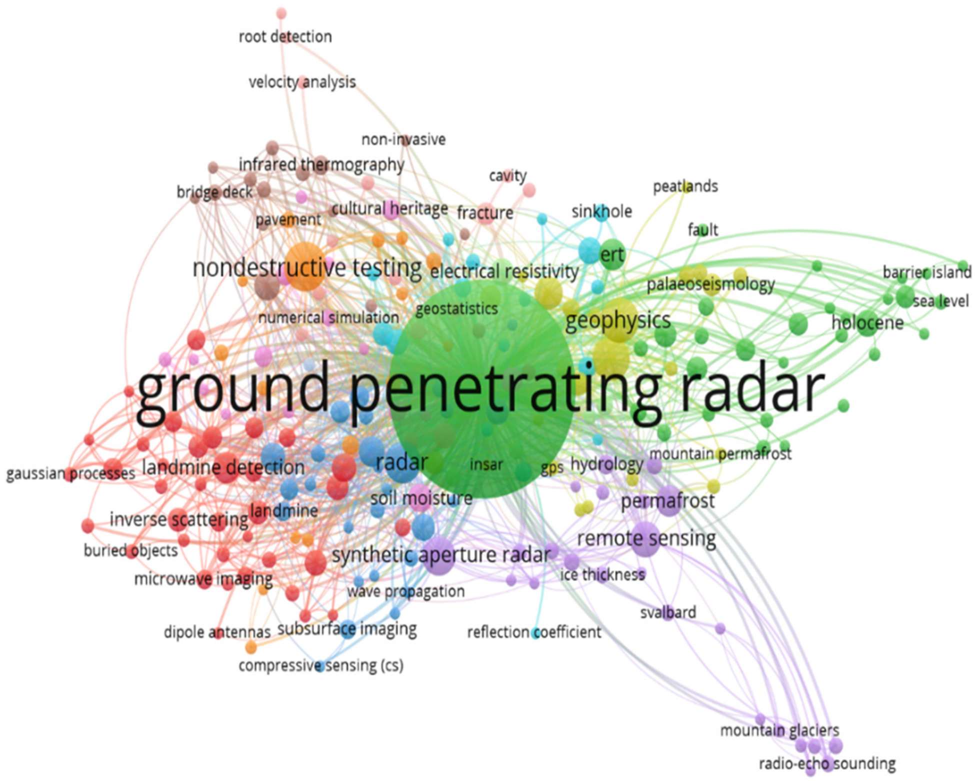

Figure 13. Co-occurrence of keywords for GPR-related studies.

With 2960 occurrences, ground-penetrating radar is the most frequent keyword (see Table 7). With 160 occurrences, the non-destructive testing keyword comes in second but is still a long way behind the first. Geophysics, electrical resistivity tomography, and radar are among the top five most frequent keywords. Regarding the average publication year, the most recent keywords include machine learning (2019.59), predictive models (2020.10), data models (2020.25), and deep learning (2020.36). On the other hand, traditional keywords include buried objects (2007.56), borehole radar (2008.80), rough surfaces (2009.25), and subsurface (2009.80). Inverse modeling (52.83), frequency domain (50.60), full-waveform inversion (43.08), seismic refraction (40.88), hydrology and buried objects (40.31) attain the highest average citations, among other keywords. Concerning the average normal citations indicator, the predictive model's keyword (13.69) is the most significant keyword in this study subject. This indicates the different applications of prediction modeling from GPR in various fields.

Table 7. Top 5 most cited keywords in GPR research between 2001 and 2021.

Keywords	Total Occurrences	Average Publication Year	Average Citations	Average Normal Citations
Ground penetrating radar	2960	2014.25	15.53	1.00
Non-destructive testing	160	2014.80	18.69	1.32
Geophysics	128	2013.50	18.34	1.02
Electrical resistivity tomography	122	2014.31	11.81	0.63
Radar	110	2010.65	21.04	0.87

4. Qualitative Analysis

The scientometric analysis provides the readers with keyword clusters without identifying the current gaps and future directions in the studied research area [47]. As a result, a qualitative discussion of the papers used in the scientometric review is conducted to provide a comprehensive classification and summarization of GPR research. It also aims at presenting the current gaps and future trends in this research field. In this research, GPR-related studies are classified based on the dedicated application. It is determined that GPR systems could be utilized in many diverse applications, including civil engineering, geological research, archaeological studies, and hydrological applications, as follows:

4.1. Civil Engineering

GPR could be widely utilized in civil engineering applications [48], including buildings [49], foundations [2], roads [50], bridges [51], railways [52], tunnels [53], landmine detection [54], pavements [8,9,55–61], and underground utilities [62–64], as follows:

4.1.1. Buildings

Buildings can be classified into different types: cultural heritage structures and modern structures. GPR is used to assess buildings and common structural components for (1) heritage preservation and building code compliance, (2) deterioration mapping, which can be used as a decision-making tool for preventive maintenance, and (3) determining the extent of structural damage (i.e., detect fractures, voids, moisture, and rebar) caused by natural disasters such as earthquakes, floods, and landslides [6]. The GPR application in building deterioration is extremely useful, especially for occupied structures. This can be attributed to the fact that GPR does not disrupt residents' and tenants' everyday activities (i.e., less intrusive), unlike other assessment methods. In addition, because building maintenance and repair are likewise costly, GPR is regarded as a useful approach to identify early problems before damage or failure is visible [65]. Despite that, the GPR application to detect the probable damage causes and support the rehabilitation of buildings after natural disasters is still very limited. Instead, the buildings are demolished or rehabilitated without using non-destructive techniques [6].

4.1.2. Foundations

There are a few studies of GPR application in substructures that examine the interaction between building foundations and the ground. Examples of these applications include: (1) detecting foundations and assessing their structural safety and integrity [66] and

(2) identifying water tables and wet ground that may induce settlement [67]. However, because of the difficulties of accessing such structures through an antenna, the number of these applications is currently limited [68].

4.1.3. Road Pavements and Bridges

Another unique application of GPR is providing subsurface information for the transport infrastructure, including roads, pavements, and bridges [69]. For road pavements, GPR surveys are conducted on flexible, rigid, semi-rigid, and composite pavements. Nowadays, the scope of these surveys is not only focused on assessing steel bars or the thickness of layers, but it is extended to conducting a structural assessment, detecting water infiltration, subsidence, voids, cracks, and anomalies [70,71]. On the other side, GPR bridge surveys are conducted either from the bridge deck or from specific bridge parts such as girders and columns [72–75]. The surveys are mostly used to diagnose bridges for detecting problems related to embedded reinforcement (e.g., bars and post-tensioned or pre-stressed tendons), corrosion and cracks [76,77], and poor compaction [78]. For the shortcomings, it is worth mentioning that GPR is still being used on an ad-hoc basis rather than regularly. Furthermore, the integration between building information modeling (BIM) and pavement management systems (PMS) is still being researched for developing integrated management and decision-making system [79,80].

4.1.4. Underground Utilities

GPR may also be used to detect the invisible and sophisticated network of underground utilities such as water supply pipes, stormwater drainage, sewers, gas pipes, power cables, communications cables, and traffic lights cables [81,82]. The mapping and scanning of underground utilities are one of the most difficult GPR activities of all civil engineering applications. This is due to the following facts: (1) radargram patterns of utility depths, orientations, and material types are frequently non-typical when compared to other infrastructures [6], and (2) the location and status of these underground utilities remain mysterious in most cities in contrast to the evident and visible damage to above-ground assets (e.g., roads and bridges). The condition deterioration of these utilities will be apparent by the occurrence of road collapse or traffic safety hazards from water leaks and seepage from water utilities, soil wash-out, and gas explosions [83,84]. Future research shall focus on GPR interpretation, particularly in extracting the hyperbolas pattern, to forecast unanticipated disturbances [82]. Another research direction incorporates examining combinations of different underground hazards under the utility networks.

4.2. Geological Studies

Identifying geological layers is necessary for locating drinking water supplies and other natural resources, as well as identifying risk zones. Furthermore, various stratigraphic and geological studies have reported significant findings concerning the Earth's surface [40,85]. Excavations are time-consuming, expensive, and frequently impossible to be conducted because some study sites are protected. As an alternative, GPR, a non-invasive geophysical technology, could be utilized to provide high-resolution subsurface imaging and map shallow formations, detect permafrost, and locate fracture or water-bearing zones [13,14,86]. It is typically used in conjunction with electrical resistivity tomography to offer comprehensive geological information. However, these geophysical technologies have not been generally evaluated and deployed because of the following reasons [6]: (1) the lack of knowledge and understanding of the capabilities of GPR in geophysics by the geotechnical engineers, and (2) the preference of the geological community to believe in the soil and rock that they can see (borehole log) over what they cannot see (radar signal). Therefore, the potential of applying GPR in geotechnical studies needs to be further examined in the future.

4.3. Archeological Applications

In archeology, GPR is capable of mapping historical buildings as well as detecting cracks, fractures, and cavities in historical sites [15,16,87]. Unlike conventional excavation methods that might destroy important archaeological structures, this subsurface imaging approach is very effective [88]. The capacity of GPR to detect the targeted buried objects is influenced by the geometry of the object of interest, subsurface geometric features, and the existence of complicated stratigraphy [89]. It has been demonstrated that soil type and density, sediment mineralogy, and moisture and clay content have a significant impact on data processing parameters and detection accuracy [90]. Other variables include topography, burial depth, and vegetation cover [89]. Therefore, it is critical to investigate and examine the burial conditions when detecting buried archaeological remains.

4.4. Hydrological Research

GPR is a potential technology for the characterization and monitoring of hydrological systems at high resolution and on a broad scale [91,92]. Object detection in the ground is affected by geological elements such as mineralogical clay, saline water, hot water, and soils [93]. The application of GPR is viable for assessing soil water content with an accurate vertical resolution and an increased spatial resolution [94]. It could also be applied in the future to examine different soil types of different sizes and gradations [95]. Furthermore, radar data may be utilized to detect the presence of liquid organic pollutants in contaminant hydrology applications [96].

5. New Avenues of GPR Applications

GPR, ERT, shallow seismic refraction (SSR), and very low frequency electromagnetic (VLFEM) are examples of the several available geophysical methods that could be utilized in the fields of civil engineering, geological research, archaeological studies, and hydrological applications. Geotechnical risks are the primary determinants of building decisions in structurally challenging zones. Different techniques, such as geotechnical techniques, geophysical tools, and remote sensing, are used and integrated to study the subsurface structures and locate any geological formations that might obstruct the development of new communities [97–99]. In the archaeological field, geophysical methods are commonly used to highlight differences in the physical behavior of the subsurface caused by the presence of buried remains [16,100,101]. Understanding the complexities of the interaction between archaeological features and their geophysical reaction will consume considerable effort. The studies revealed that integrating geophysical approaches can offset these limitations and improve the reported findings. For hydrological applications, geophysical investigations are carried out to demonstrate the capacity of technologies for detecting cavities, sinkholes, and water infiltration pathways [102].

It is demonstrated that satellite radar remote sensing systems can be applied to complement non-destructive ground-based techniques (e.g., GPR), paving the way for the smart monitoring of infrastructure assets. The combination of these approaches enables the high resolution, flexibility, and capacity of GPR to detect the sources of shallow defects to be paired with the ability of satellite remote sensing to simulate the evolution trend of distresses on a broader scale. Indeed, the increased precision can help to increase a facility's resistance to both external catastrophes and internal degradation, thus leading to infrastructure resilience [103–105]. The groundwater potential of complex areas characterized by moderate to steep slopes of topography, strong heterogeneity, multiple intrusions, and repetitive deformations could be assessed using a joint venture of satellite remote sensing, geoelectrical resistivity, and GPR techniques [106]. The integrated approach of remote sensing, sedimentological, and geophysical approaches has been proven to be accurate and successful in the mapping of paleochannels and accomplishing sustainable groundwater development goals [107]. Another important application has been reported by the combination of field observations, geophysical tools, and satellite remote sensing for landslide characterization [108]. The integration of various remote sensing techniques could be utilized for detecting and inspecting buried archaeological remains as well as assessing their preservation degrees [109,110].

The classic GPR system suffers from low detection efficiency and high labor costs when the detection field is vast. Furthermore, the GPR application could be dangerous for field investigations in harsh weather and terrain conditions. In an attempt to overcome these shortcomings, an integrated system of the unmanned aerial vehicle (UAV)-mounted GPR is developed to examine regions without being in direct contact with the Earth. This system is beneficial for spotting and detecting destructive objects such as landmines or archaeological surveys [111–114].

Future studies shall focus on automating GPR scanning operations. At the current time, several parts of the scanning process are performed manually, being labor-intensive and consuming considerable time. Furthermore, the output formats of different scanners are not uniform, and the data cannot be simply imported into a general-purpose 3D modeling software such as Autodesk Revit. This calls for the necessity of exploring other options for solving this problem [3]. In civil applications, future studies might explore using GPR in pavement design and maintenance procedures. The focus shall be given to examining the drawbacks, including the method's accuracy and the difficulty in interpreting recorded signals [115]. In the archaeological field, it is suggested to integrate geophysical data to acquire volumetric and planimetric structures in the subsurface, necessitating the use of advanced algorithms (i.e., machine learning algorithms and image data fusion) [100].

In the recent few years, satellite-based interferometry has been leveraged for analyzing and monitoring structural deformation in bridges. Wang et al. [116] used persistent scatters interferometric synthetic aperture radar (PS-InSAR) technology to scrutinize the collected time series data and detect differential deformation between piers. In this regard, they built a three-dimensional deformation model using green's function-based interpolation method. In another study, Schlögl et al. [117] experimented with the use of airborne laser scanning (ALS), vehicle-mounted mobile laser scanning (MLS), and satellite radar interferometry (InSAR) for identifying structural deformation trends. They elucidated that three non-invasive technologies were able to monitor deformation, with ALS offering a more flexible and cost-effective approach than MLS. In addition, InSAR was found to stand out as a more efficacious technology for long-term deformation assessment of bridge structures. Impact echo was lately exploited by Hu et al. [118] for defect detection in ballastless tracks. They utilized the finite-difference time-domain (FDTD) technique to emulate the propagation of elastic waves in ballastless tracks, and an improved synthetic aperture focusing technique (SAFT) was presented for the visualization of defects. In a study by Stüwe et al. [119], impact echo and ultrasonic contact testing were implemented to investigate scaling growth in geothermal pipelines. They evinced that both tests are applicable, while impact echo offered a rapid and more cost-efficient scaling monitoring alternative.

Electrical resistivity tomography (ERT) is another non-destructive technique that was newly deployed by Abudeif et al. [120] to find groundwater pathways and observe their level rise. In this context, ERT was able to create 3D profiles and 3D voxel interpretations for subsurface geoelectrical zones. As well, Guo et al. [121] jointly employed self-potential and electrical resistivity tomography for the sake of seepage detection in earth-filled dams. They managed to reestablish pseudo-3D seepage pathways by combining the measurements of electrical resistivity alongside inversion outcomes of self-potential data. An infrared thermography camera is a contactless non-destructive technique that was mounted by unmanned aerial vehicles (UAV) and used by Zhou et al. [122] for the sake of automated detection of earth embankment leakage. In their study, an AlexNet-based transfer learning framework was created for the classification of infrared images into either cold slope leakage, warm slope leakage, normal slope, normal ponding, cold piping, and warm piping. Moreover, Loiotine et al. [123] utilized airborne infrared thermography for characterization of rock mass in complex conditions. By analyzing thermograms, they succeeded in mapping the correlation exhibited between rock mass properties and temperature profiles.

6. Conclusions

The research study applied a holistic approach of bibliometric and scientometric assessment to present a global overview of ground penetrating radar (GPR) research from 2001 to 2021. The Web of Science database produced 6880 publications that were examined with respect to the publication trends, sources of publications and subject categories, cooperation of countries, the productivity of authors, citations of publications, and clusters of keywords. According to the findings, there has been a shift in the development and promotion of the field of GPR. The number of annual publications had climbed from 139 in 2001 to 576 in 2021. Specifically, the publishing output has risen rapidly since 2006, with a multidisciplinary and multi-regional approach distinguishing it. The research studies were published in 894 journals, with the number of active journals rising from 68 in 2001 to 215 in 2021. The number of subject categories included in GPR-related research fluctuated during the study, ranging from 38 in 2001 to 68 in 2021. The GPR research studies involved 118 countries from all around the world. The United States and the People's Republic of China made the most significant contributions to the research community. The Chinese Academy of Sciences, China, was the most prolific institution, followed by the National Research Council, Italy. "Modelling ground penetrating radar by GprMax" article that was authored by Giannopoulos [33] in the *Construction and Building Materials* journal and was the top most cited article (409 citations). Ground-penetrating radar, non-destructive testing, geophysics, electrical resistivity tomography, and radar ranked first through fifth in terms of emerging keywords. GPR was widely applied in four different fields; civil engineering (landmine detection, bridge deck, and asphalt pavement), geological research (sedimentology, stratigraphy, and Holocene), archaeological studies (archeology, cultural heritage, and geoarchaeology), and hydrological practices (soil moisture, soil, and moisture content). All of these findings and conclusions have been interpreted in light of the Web of Science database. This review article could assist academics in identifying the most prestigious journals and researchers with whom to collaborate or publish in the future. It also aided in recognizing current hotspots in order to gain a comprehensive understanding of the subject at hand.

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